UCRL- 92351
PREPRINT

A Comparison of Projectile Penetration and a Cone Penetrometer as Methods for Measuring Tuff Strength

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This paper was prepared for submittal to
3rd Containment Symposium
Idaho Falls, Idaho
September 9-13, 1985

August 1985

Lawrence Livermore National Laboratory

A COMPARISON OF PROJECTILE PENETRATION AND A CONE PENETROMETER AS METHODS OF MEASURING TUFF STRENGTH

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ABSTRACT

Most methods of predicting the effects of underground nuclear explosions require, as input, estimates of the strength of the medium in which the effects occur. At present there is no _in situ_ method of measuring this strength. We have tested two methods that could be adapted for use on the walls of large boreholes in tuffs at the surface at NTS.

The first method--depth of penetration of a projectile--has been studied extensively by projectile designers, who found that the depth of penetration is inversely proportional to $(\rho Y)^{1/2}$, where ρ is the bulk density and Y is the unconfined compressional strength. We fired projectiles at tuffs in seven locations in the NTS area. Strength and density were measured on core samples. The measurements showed a great deal of scatter, but mean results from the seven sites gave a reasonable linear fit to both $(\rho Y)^{-1/2}$ and to strength itself.

The second method--force on the tip of a cone penetrometer--has been studied for many years by soils engineers, but evidently has never been investigated in rock. There are many semiempirical relationships between force and various soil properties, but not strength _per se_. We were able to test a cone penetrometer at only three of the seven projectile locations, and one other location. Since, however, we measured both force and strength vs

depth, we obtained many examples of force vs strength. We made several penetrations at each location. At most depths, the range of force was large. The mean force observed over a 15 cm depth range does not appear to have any relation to the strength at that depth range.

Consequently, even though it is easier to measure force on the cone than depth of penetration of a projectile into the wall of an emplacement hole, the projectile method appears to be the method of choice for further development.

INTRODUCTION

One of the most important input variables in calculating the effects of underground nuclear explosions is the shear strength of the medium in which the effects take place. Terhune (1978) considered strength the most important factor in the development of the "containment cage"--or residual compressive hoop stress--surrounding the pressurized cavity. He calculated the stress in the containment cage for situations with different constant shear strengths, and showed that stress is a function of strength.

Because a single value of shear strength will aid in evaluating the containment of an event, any _in situ_ method for measuring strength, even if not as a function of confining pressure, would be very valuable. At zero confining pressure, the shear strength is equal to half of the compressional strength, so a measurement of unconfined compressional strength is an adequate in situ measurement.

We have investigated two possible methods of measuring unconfined compressional strength in place: the penetration of a projectile, and the force on the tip of a cone penetrometer. We wished to determine which, if either, of these methods is worth pursuing as a downhole system.

We shall first describe some background for each of these methods, then describe our experimental technique, and finally present some results.

BACKGROUND

Projectile Penetration

Penetration of projectiles into earth materials has been of interest to weapons developers for centuries. In recent decades a great deal of work has been done, especially by Sandia and the Waterways Experiment Station, with projectiles dropped from diving aircraft and fired from gas guns. Some of the reports of this and similar work are of interest to us.

Thigpen (1966), working with blunt projectiles, found that deceleration was proportional to the strength of the target, and the depth of penetration was proportional to $(\rho/Y)^{.22}$, where ρ is the density of the target and Y is the unconfined compressional strength. Caudle et al. (1967) used penetration to distinguish different types of soil. They plotted deceleration as a function of depth, and detected interfaces by sudden changes in deceleration. Young (1969) developed a formula for depth of penetration that involved a "soil constant" S, which was determined empirically for each soil type. The dependence of S on the properties of the soil, however, was not established. Rohani (1972) found that the depth of penetration was proportional to target strength.

One of the most interesting studies was a series of calculations by Butler (1975), in which he showed that if the projectile velocity and properties were held constant, the depth of penetration and deceleration depended strongly on the unconfined compressional strength and the "locked" volume strain ρ/ρ_o. Here ρ_o is the initial bulk density and ρ is the bulk density after the voids have been squeezed out of the soil. Penetration and deceleration do not, however, depend strongly on either ρ or ρ_o alone. Wagner et al. (1976) obtained similar results from a parameter study.

Even more interesting was an empirical expression found by Bernard (1978), who obtained a formula for depth of penetration of a conical projectile such that:

$$D = \frac{0.2\ V\ M}{A\ (\rho Y)^{1/2}} \left[\frac{100}{RQD} \right]^{0.8} ,$$

where V is the projectile's velocity, M its mass, and A its cross-sectional area, and RQD is the "rock quality designation", first described by Deere (1964) in terms of the length of pieces in the rock cores.

These results imply that under the right circumstances D can be used as a measure of Y. Consequently, it seemed a good idea to try to correlate depth of penetration with strength in NTS material.

Cone Penetrator

The soil mechanics literature gives little support to the idea that strength can be measured with a cone penetrometer. A respected soil mechanics text (Wu, 1969) says:

> "[Penetrometers] measure the resistance of a soil in situ against penetration by a standard device. This resistance usually gives some indication of the strength and compressiblity of the soil ...[Penetration]... can be correlated with the significant physical properties such as density and shear strength. Since all such correlations are entirely empirical, their reliability is dependent upon the amount of data that has been collected. Furthermore, these empirical relations are affected by a great many factors, such as the soil type, the moisture content of the soil, and the depth at which

the [penetration] is made. Since only the most important factors can be taken into account, these correlations are always approximate in nature. So far, relatively constant correlation has been obtained only for cohesionless soils."

An important text on the penetrometer (Sanglerat, 1972) gives the expression

$$q_c = 1.3 \left[P_0 \tan^2 \left(\frac{\pi}{4} + \frac{\varphi}{2}\right) e^{\pi \tan \varphi} + \frac{c}{\tan \varphi} \left[\tan^2 \left(\frac{\pi}{4} + \frac{\varphi}{2}\right) e^{\pi \tan \varphi} - 1\right] \right],$$

where q_c is the force per unit area, P_0 is the overburden pressure, c is the cohesion (or intercept of the strength curve), and φ is the angle of internal friction (or slope of the strength curve). But there is no evidence that this can be solved for the variables of interest. The text discusses only the case where c = 0 and φ can be guessed. Nowhere else in this large text on the penetrometer is there any discussion of measurement of strength.

Consequently, at first it seemed unlikely that a cone penetrometer could be used. But Serata (1983) found that the force on a penetrometer was proportional to strength both in soft mortar and in several hard rocks. Since Applied Research Associates had developed a truck-mounted penetrometer suitable for use in alluvium and tuff, we considered it worthwhile to see if the force on that penetrometer could be correlated with strength.

EXPERIMENTAL METHOD

Projectile Penetration

We used a seismic source called the "Betsy" as a projectile accelerator. It consists of an eight gauge shotgun mounted vertically on a horizontal plate. The plate in turn is held above the ground by an ordinary rubber tire laid horizontally below it. The whole apparatus is mounted on the chassis of a wheelbarrow for transportation. Fig. 1 is a photograph of the Betsy. The shotgun fires an iron slug vertically into the ground. The slug, weighing 84 g, has a muzzle velocity specified to be 530 m/s. It is 4 cm long, with a flat face, 1.5 cm in diameter; 1.5 cm behind the face, the diameter abruptly increases to 2 cm.

We measured the depth of penetration by inserting a 1-mm-diameter welding rod into the hole made by the projectile and attempting to feel the top of the projectile at the bottom of the hole. We used a finger to mark the point at which the rod intersected the surface of the ground. We then withdrew the rod, and measured the distance from the bottom to the finger with a steel tape. We estimate the error to be about 5 mm. Rubble often blocked the passage of the rod into the hole, and then twisting was required to reach what appeared to be bottom. This would reduce accuracy. If the projectile bounced out of the hole (as it often did for the stronger media), we subtracted 4 cm from the measured depth to account for the length of the projectile.

We made measurements at two to four outcrops a few meters apart at each of nine locations, seven at NTS and two at the Tonopah Test Range.

Cone Penetrometer

We used a cone penetrometer built and operated by Applied Research Associates (ARA). They describe it as follows (Blouin, 1985):

"The electric cone penetrometer consists of an instrumented probe which is forced into the ground using a hydraulic load frame mounted on a heavy truck. The truck serves as a reaction mass. The probe consists of a conical tip and friction sleeve which provide independent measurements of vertical resistance beneath the tip and frictional resistance on the side of the probe as functions of depth. ... A schematic view of the penetrometer assembly is shown in Fig. 2. The penetrometer is of standard dimensions, having a 1.405 in (3.568 cm) diameter, 60° conical tip, and a 1.405 in (3.568 cm) diameter by 5.25 in (13.33 cm) long sleeve. The penetrometer is advanced vertically into the underlying soil at a constant rate of 48 in/min (2 cm/s), although this rate is reduced as hard layers are encountered."

"Internal strain gaged load cells measure the vertical resistance against the conical tip and the side friction along the sleeve. The friction sleeve and tip are physically independent, though the load cell monitoring the sleeve measures the sum of the friction force and the tip force. The load cell data are transmitted from the point assembly to the onboard computer via a cable running through the push tubes. The analog data are digitized, recorded, and plotted in the penetrometer truck. A set of data was recorded each second on all tests."

In practice, since the tuff layer was hard, the penetration rate was much less than 2 cm/s, even though the truck was weighted with several thousand kilograms of lead shot. Penetration stopped when the truck, with a total weight of about 18000 kg, lifted off the ground.

The data are plotted as profiles of tip resistance and sleeve friction. Tip resistance, the quantity used in this study, is obtained by dividing the vertical force on the tip by the effective tip area, 10 cm^2. Tip resistance (or stress) is plotted as a function of depth.

We made penetration tests at three of the seven NIS sites (we couldn't get the truck into the others) and again made several penetrations at each of several outcrops. We also tested at one site not studied with the projectile.

Sampling

Cores at the NTS sites were taken by Holmes and Narver (H&N), using a 7.5 cm core barrel a month or two after the penetrometer tests. A 30-cm-long barrel was used at each NTS site, and the drillers attempted to core near the projectile holes. These samples were then tested for strength. Unfortunately, the technicians forgot to measure density, so new samples, picked up at the sites some time later, were used for density measurements. Since it rained between the penetration tests and the density sampling, there is considerable uncertainty in the density because we do not know the saturation of the samples.

After the penetrometer tests, new cores were taken, using a 7.5-cm-diameter, 90-cm-long core barrel. More effort was made to core near the penetrometer holes. Again, however, more than a month elapsed between penetration and sampling.

Strength Measurements

The unconfined compressional strength of first set of samples at NTS was measured by Holmes and Narver (H&N). They were only able to obtain strengths at four of the seven sites; no data will be reported from the other three. Strengths for the two Tonopah sites (Cooley, 1979) were supplied to us by M. Hightower of Sandia Laboratories. The strength of the second set was measured on 15 cm depth intervals by (ARA) using standard unconfined compression techniques. They plotted volumetric, radial, and axial strain vs axial stress, and strength was obtained from the peak of those curves.

Site Descriptions

Eight sites in the NTS tuff were used for projectile penetrations. We have designated them Sites 1 through 8:

- Site 1: Tunnel Beds tuff: Light yellow reworked and bedded tuff, strongly altered to zeolite. It contains few lithics and sparse crystal fragments of sanidine and biotite. It is located in the materials yard below T tunnel at the foot of Rainier Mesa.
- Site 2: Grouse Canyon airfall tuff: Yellow-green airfall tuff that is altered to zeolite. It is poorly indurated and contains practically no lithics or crystal fragments. Although altered the structure of the pumice fragments is very evident. It was taken from the edge of the North Rainier Mesa Road above T-tunnel portal.
- Sites 3, 4,5 Bedded tuff between Ammonia Tanks tuff and Rainier Mesa Tuff. Located at the top of Aqueduct Mesa. Coring attempts were made with both air and water, but the cores disaggregated and not enough core remained for good testing. No data from these sites are reported here.
- Site 6: Ammonia Tanks tuff: Light tan non-welded basal portion. It is moderately indurated and is pumiceous and contains abundant crystals of quartz, sanidine, and biotite. Found on Aqueduct Mesa.
- Site 7: Ammonia Tanks tuff: Tan welded ash flow tuff. It is partially devitrified and contains abundant quartz, sanadine, and biotite crystals. Found on Aqueduct Mesa.
- Site 8: Paintbrush Tuff: Pale tan bedded and reworked; small pumice fragments are very abundant, biotite and magnetite are sparse, quartz and sanidine fragments are rare.. Found on Stockade Pass, junction of Holmes and Stockade Wash Roads.

An additional tuff site, called T4, was used for the cone penetrometer.

- Site T4: Tiva Canyon tuff: Medium brown ashflow tuff. The site tested is very near the distal end of the flow and the test was conducted in the unwelded top that contains moderately common small pumice fragments and sparse lithics and crystal fragments of quartz, sanidine, and biotite. It was on the top of Holmes Road.

Two other sites on the Tonopah Test Range were used for projectile penetration:

- Site A: Antelope tuff on the Tonopah Test Range: Pale buff non-welded ashflow tuff, fine grained, very uniform in strength and texture.
- Site S: Sidewinder tuff on the Tonopah Test Range: Dark brown densely welded ashflow, fine grained, very hard.

RESULTS

Strength and Density

Table 1 shows the strength of the samples for the cone penetrometer as a function of depth measured by ARA, and minimum, maximum, and mean strength of the samples for the projectile, measured by H&N. For sites 2 and 8, agreement is very good. For site 1, H&N obtained values about 60% higher than ARA. These results indicate that the strengths measured by the two agencies are fairly consistent; we may legitimately try to associate the H&N strengths with the ARA penetration data.

Table 2 shows the density data. Again, the agreement is fairly good, especially considering our ignorance of the water content in the H&N data.

Projectile Data

Table 3 shows the minimum, maximum, and mean depths of penetration of the projectile at each site. At some sites the range of depths is very great, at some, small. This difference is likely caused by variablity in the rock.

Figure 3 is a plot of penetration vs unconfined compressional strength. The regression line is

$$D = 36.42 - 1.75\ Y,$$

where D is depth of penetration and Y is strength. Figure 4 is a plot of penetration vs $(\rho Y)^{-1/2}$, with

$$D = 84.77\ (\rho Y)^{-1/2} - 8.75.$$

There is not much to choose between these fits, so it seems plausible for the present to use Fig. 3. Evidently the uncertainty in the strength and scatter in the penetration is large enough that we can consider linear regression adequate to describe the data.

Cone Penetrometer

Figures 5a and b show typical plots of tip stress vs depth at Site 1, and Figs. 6a and b show similar plots at Site 8. Clearly, at a given depth at a given site, there is a great deal of variation in the tip stress. We graphically integrated the stress over the same 15 cm depth intervals for which strengths were measured to get the mean stress for each interval. These results are shown in Table 4. The means of the stresses for each depth interval at each site are also shown.

Neither the individual measurements nor the means can be related in any simple way to the strength, although at one site there is a fairly consistent trend. A plot of stress vs strength exhibits no useful relationship.

DISCUSSION

It appears that the projectile is quite promising as a measure of in-situ unconfined compressional strength. It appears that at low strength one can use the projectile to measure strength within a factor of two, and at high strength within 30%. More to the point, mean depth of penetration seems linear with mean strength to within about 3 MPa (30 bars) or better.

The cone penetrometer does not appear useful. Work is being done to measure the confined strength of the penetrometer samples; perhaps that will give a better relation to stress. There is some evidence for correlation of compressibility with tip stress at Site 8.

Consequently, we plan to pursue the development of a method of measuring depth of penetration (or perhaps deceleration) in a big hole. We expect to design a launcher more suitable than a shotgun, and try to optimize the shape of the projectile. We shall then calibrate the method on large blocks of material of known strength, such as ice and grout. Following this, we will test the method on outcrops and, if the results can be correlated with strength, we will then build a downhole system.

ACKNOWLEDGEMENT

Work performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under Contract Number W-7405-ENG-48

REFERENCES

R. S. Bernard, "Depth and Motion Prediction for Earth Penetrators", U. S. Army Engineer Waterways Experiment Station Technical Report S-78-4, 1978

S. E. Blouin and J. S. Noel, Applied Research Associates, Internal Report to LLNL, 1985

D. K. Butler, "An Analytical Study of Projectile Penetration in Rock", U. S. Army Engineer Waterways Experiment Station Technical Report S-75-7, 1975

W. N. Caudle, A. Y. Pope, R. L. McNeill and B. E. Margason, "The Feasibility of Rapid Soil Investigations Using High-speed Earth-penetrating Projectiles", Int. Symp. on Wave Propagation and Dynamic Properties of Earth Materials, Albuquerque, August 1977

C. H. Cooley. Terra-Tek, Personal Communication to M. Hightower, 1979

D. U. Deere, "Technical Description of Rock Cores for Engineering Purposes"; <u>Rock Mechanics and Engineering Geology, International Society of Rock Mechanics</u>, Vol. 1, 1964

B. Rohani, "High Velocity Fragment Penetration of Soil Targets", Proc. Conf. on Rapid Penetration of Terrestrial Materials, Texas A&M University, 1972

G. Sanglerat, "The Penetrometer and Soil Exploration", Elsevier, 1972, p. 122

S. Serata, "Development of In-situ Property Measuring System" Serata Geomechanics internal report, 1983

R. W. Terhune, "Analysis of Burial Depth Criteria for Containment", Lawrence Livermore National Laboratory Report UCRL-52395, 1978

L. Thigpen, "Penetration of a Projectile into Pseudo Soils", Sandia National Laboratories Report SC-TM-66-562, 1966

M. H. Wagner, C. C. Fulton, and K. N. Kreyenhagen, "Parametric Study of the Effects of Target Properties, Projectile Design, and Impact Conditions on Earth penetration Processes" California Research and Technology Report DNA 4160T, 1976

T. H. Wu, "Soil Mechanics", Allyn and Bacon, 1969, p. 381

C. W. Young, Depth Prediction for Earth-penetrating Projectiles, <u>Jour. Soil Mechanics and Foundations Division,</u> vol 95, p. 803, 1969

TABLE 1 SAMPLE STRENGTHS

Site	ARA Samples for cone penetrometer, Depth m: 0 - .15	.15 - .3	.3 - .45	.45 - .6	.6 - .75	.75 - .9	H&N Samples for projectile: Min	Max	Mean
	Strength, MPa								
1	10.3	13.8					14.5	22.7	19.0
2					2.4		2.1	3.4	3.0
6							7.3	7.9	7.5
7							18.7	19.4	19.2
8	4.3	3.5	3.6	3.9	3.3	3.3	3.2	3.9	3.4
T4	5.8	4.4	8.4	5.4	10.				
A							13.	17.	50.
S							30.	70.	50.

TABLE 2 DENSITY OF SAMPLES

Site	ARA Samples for cone penetrometer, Depth m: 0 - .15	.15 - .3	.3 - .45	.45 - .6	.6 - .75	.75 - .9	H&N Samples for projectile: Min	Max	Mean
	Density, g/cc								
1	1.69	1.78					1.58	1.82	1.7
2					1.42		1.08	1.39	1.23
6							1.34	1.58	1.46
7							1.74	2.04	1.89
8	1.55	1.48	1.47	1.51	1.49	1.54	1.34	1.61	1.46
T4	1.36	1.30	1.42	1.49	1.46				
A							1.65	1.75	1.70
S									1.89

TABLE 3 PROJECTILE PENETRATION (cm)

Site	Min	Max	Mean
1	3.8	7.6	5.1
2	34.3	36.8	35.6
6	21.6	33.	26.9
7	3.2	4.4	3.5
8	17.1	34.3	24.6
A	5.1	8.9	6.1
S	0.	0.	0.

TABLE 4 CONE PENETRATOR TIP STRESS

	Depth, cm					
Site	.03 - .15	.15 - .3	.3 - .45	.45 - .6	.6 - .75	.75 - .9
	Stress, MPA					
1a	90.3	43.4	26.2			
1b	76.5	34.5	16.5			
1c	90.3	65.5	20.7			
1d	44.1	18.6				
1 mean	75.3	40.5	21.1			
2a	42.0	62.0	67.6			
2b	49.6	70.0				
2c	44.8	68.2	67.6			
2d	44.1	68.2	69.6			
2 mean	45.1	67.1	68.3			
8a	45.5	33.7	19.3	46.8	105.5	
8b	51.7	35.2	39.3	49.6	74.4	
8c	29.6	24.1	69.6	82.7		
8d	37.2	31.7	61.3	84.1	88.2	66.2
8e	76.5	80.0	56.5	25.5	26.2	75.8
8 mean	48.1	40.9	49.2	57.7	73.6	71.0
T4a	46.8	51.0	85.5	95.8	111.0	118.5
T4b	53.1	77.2	89.6	106.2	124.	
T4 mean	50.	64.1	87.5	101.	117.5	118.5

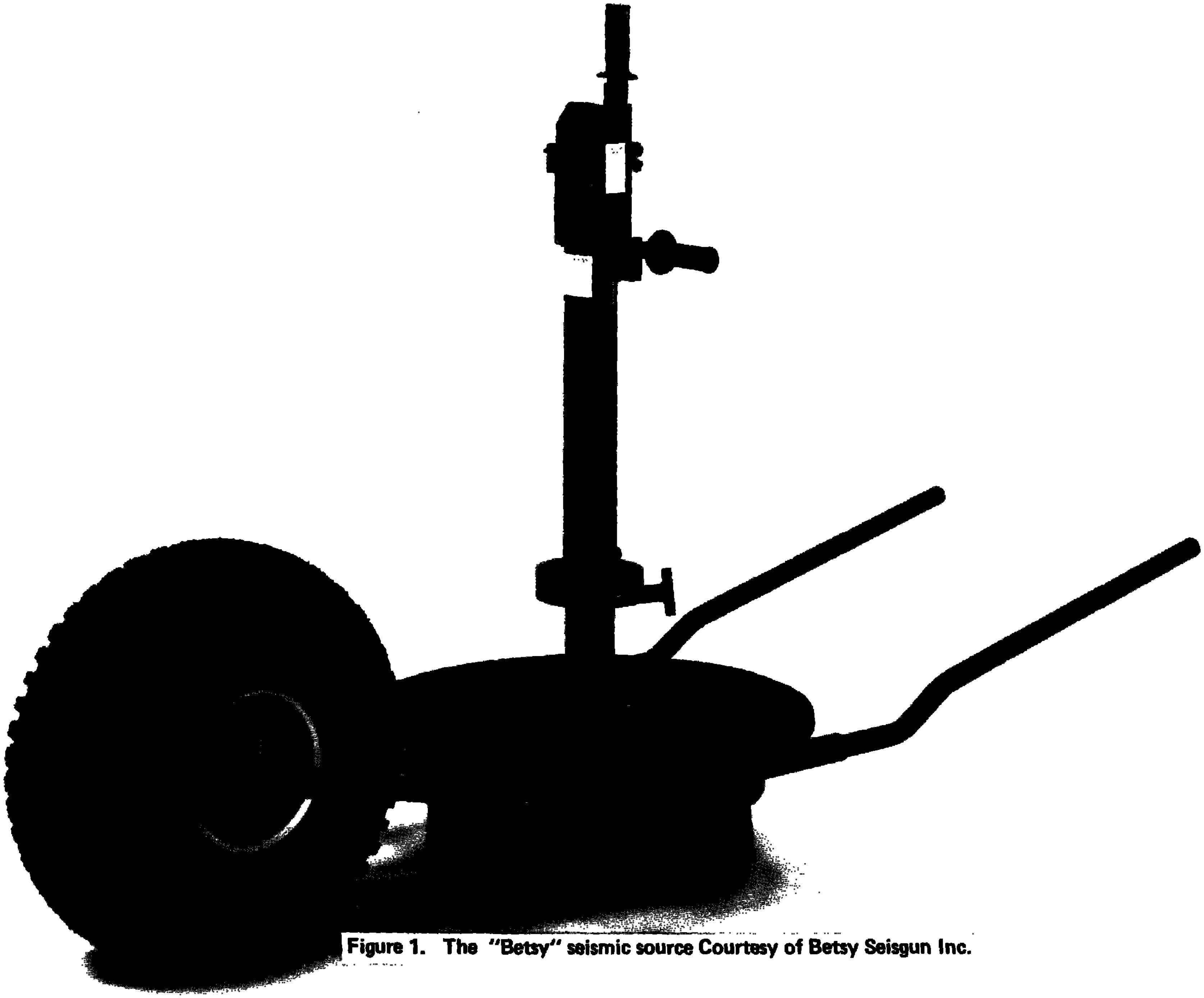

Figure 1. The "Betsy" seismic source Courtesy of Betsy Seisgun Inc.

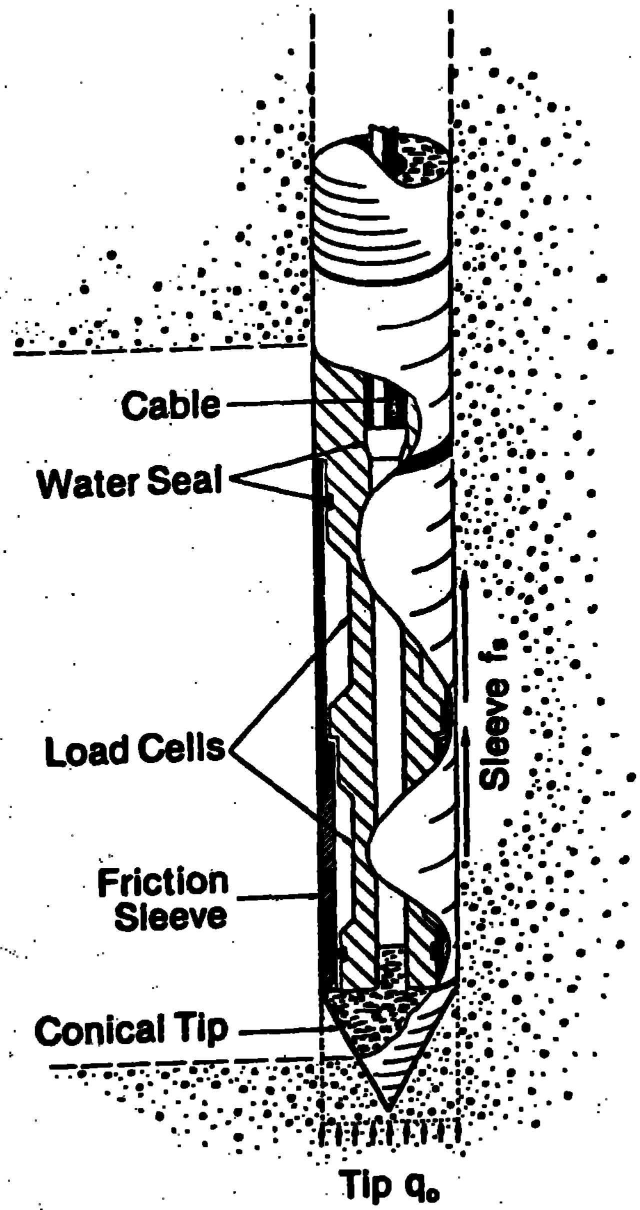

Figure 2. Schematic view of ARA high capacity cone penetrometer.

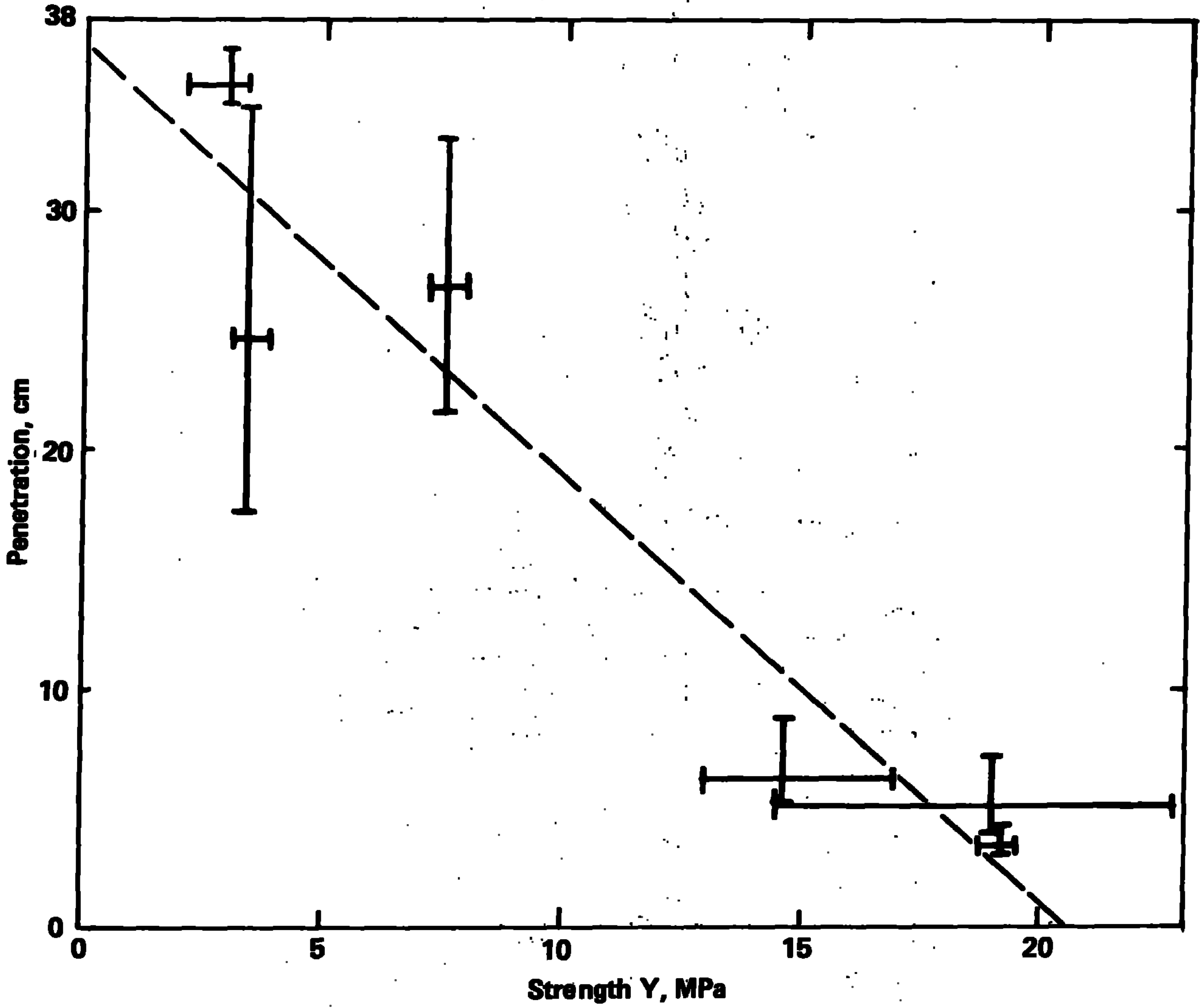

Fig. 3 Depth of projectile penetration vs unconfined compressional strength.

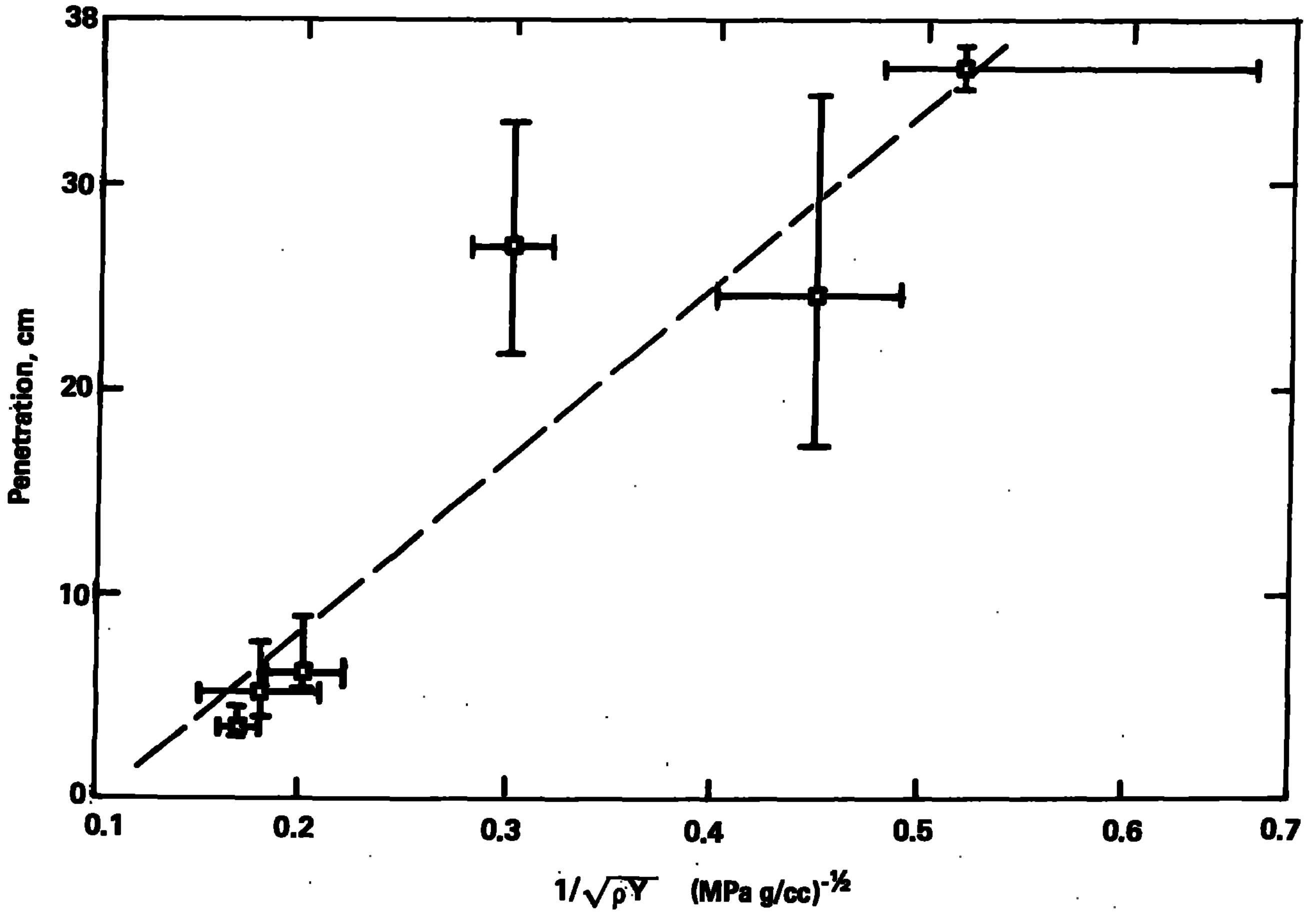

Fig. 4 Depth of projectile penetration vs $(\rho Y)^{-1/2}$

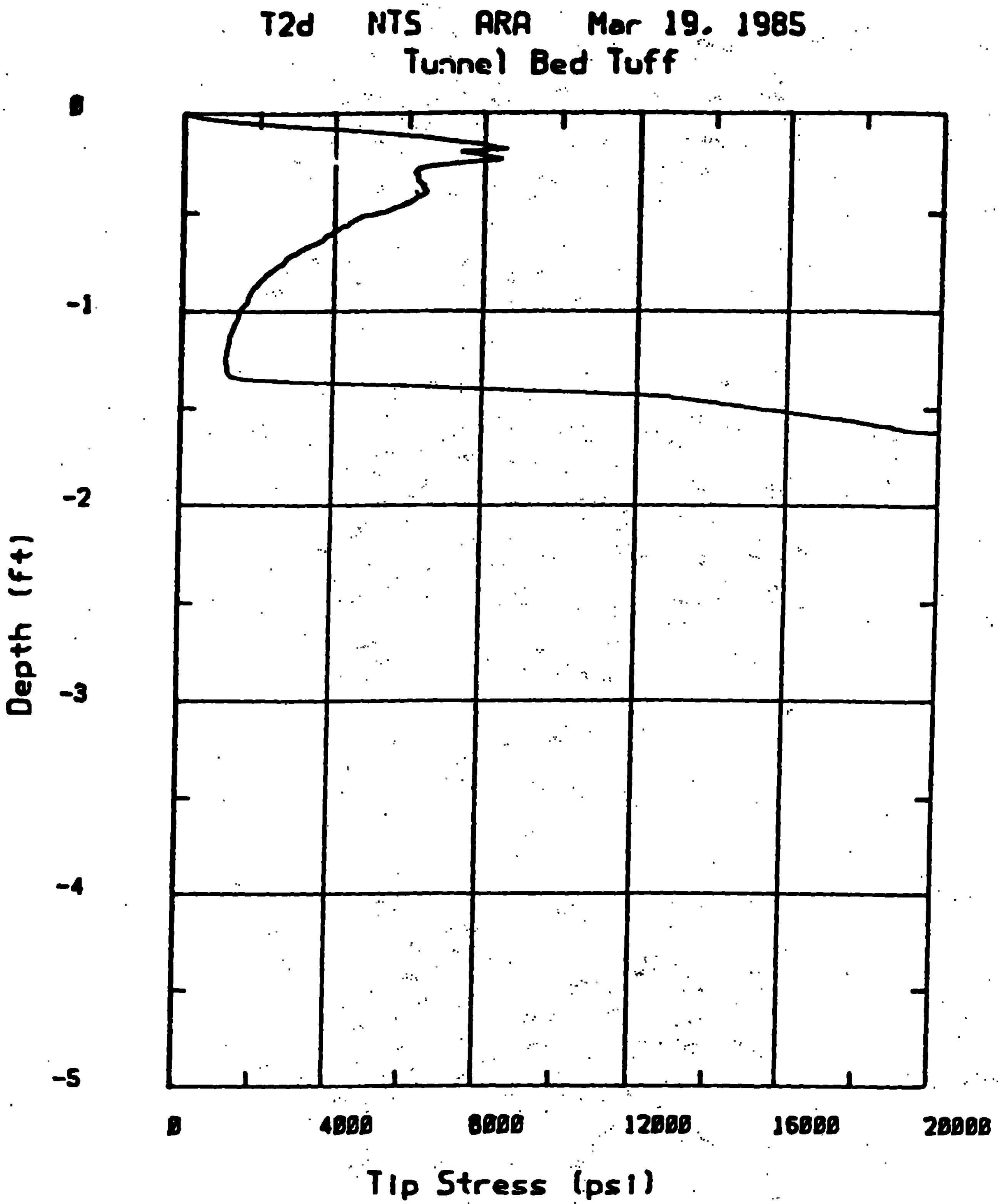

Figure 5a. Penetrometer tip stress vs depth for site 1

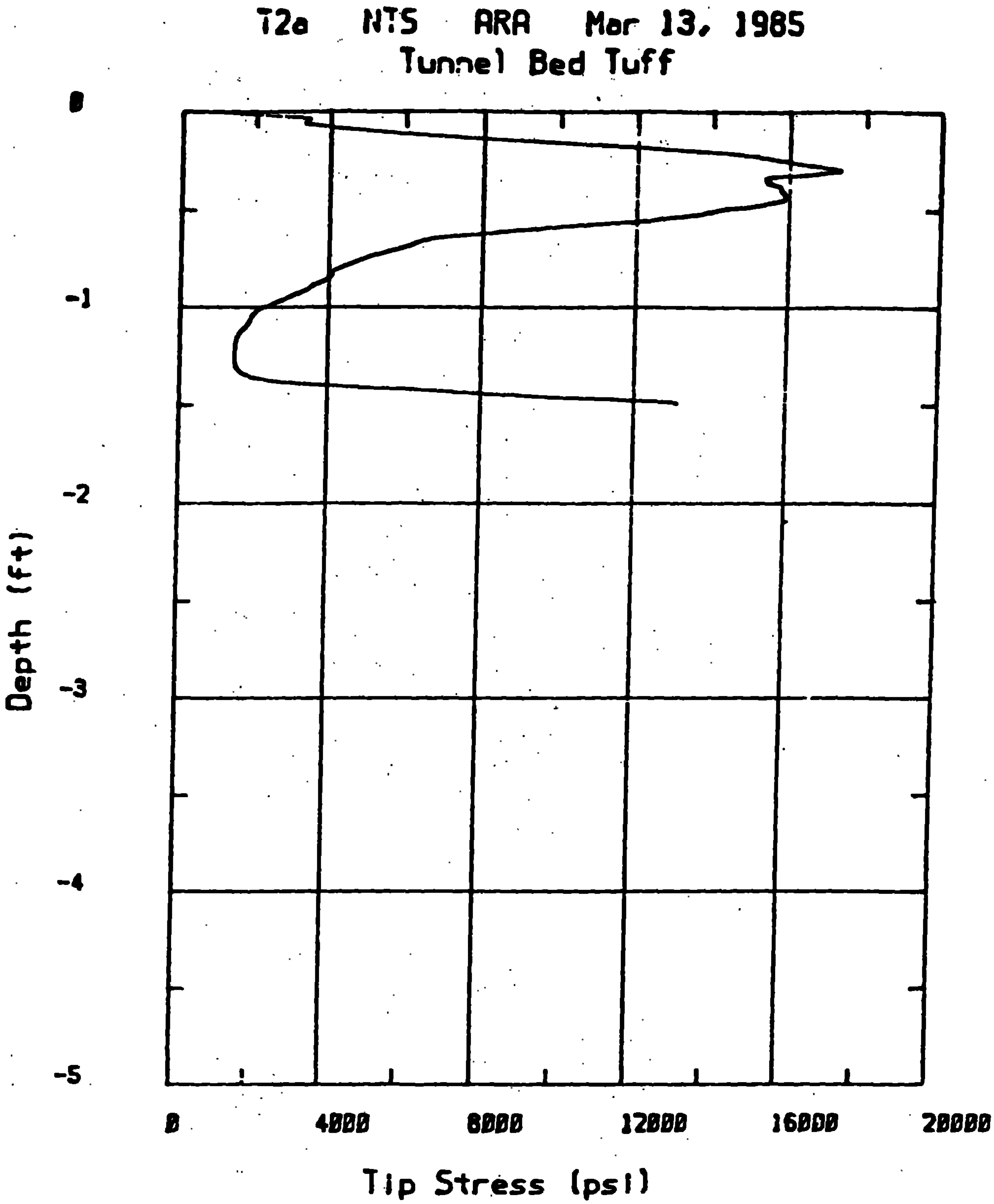

Figure 5b. Penetrometer tip stress vs depth for site 1

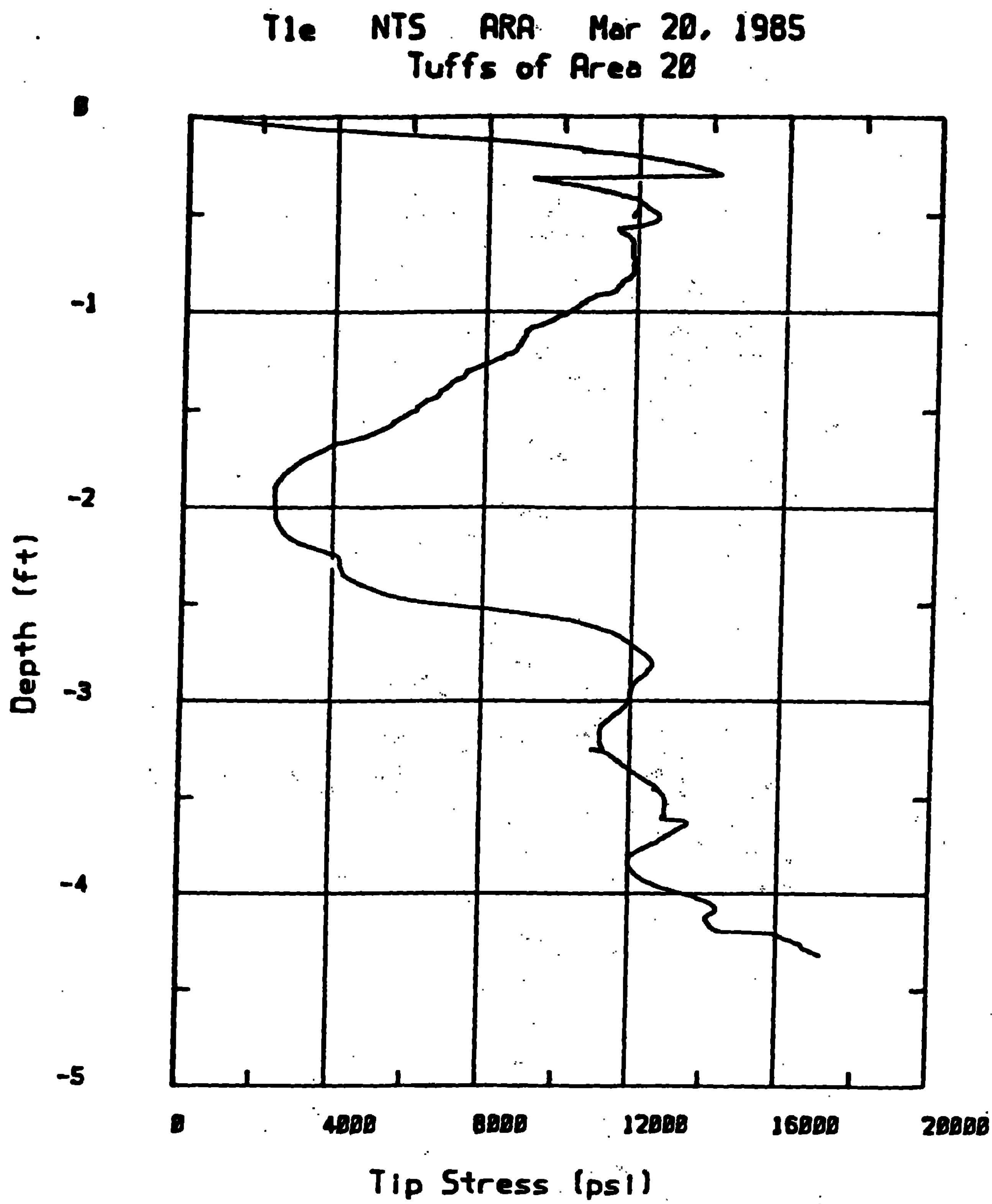

Figure 6a. Penetrometer tip stress vs depth for Site 8

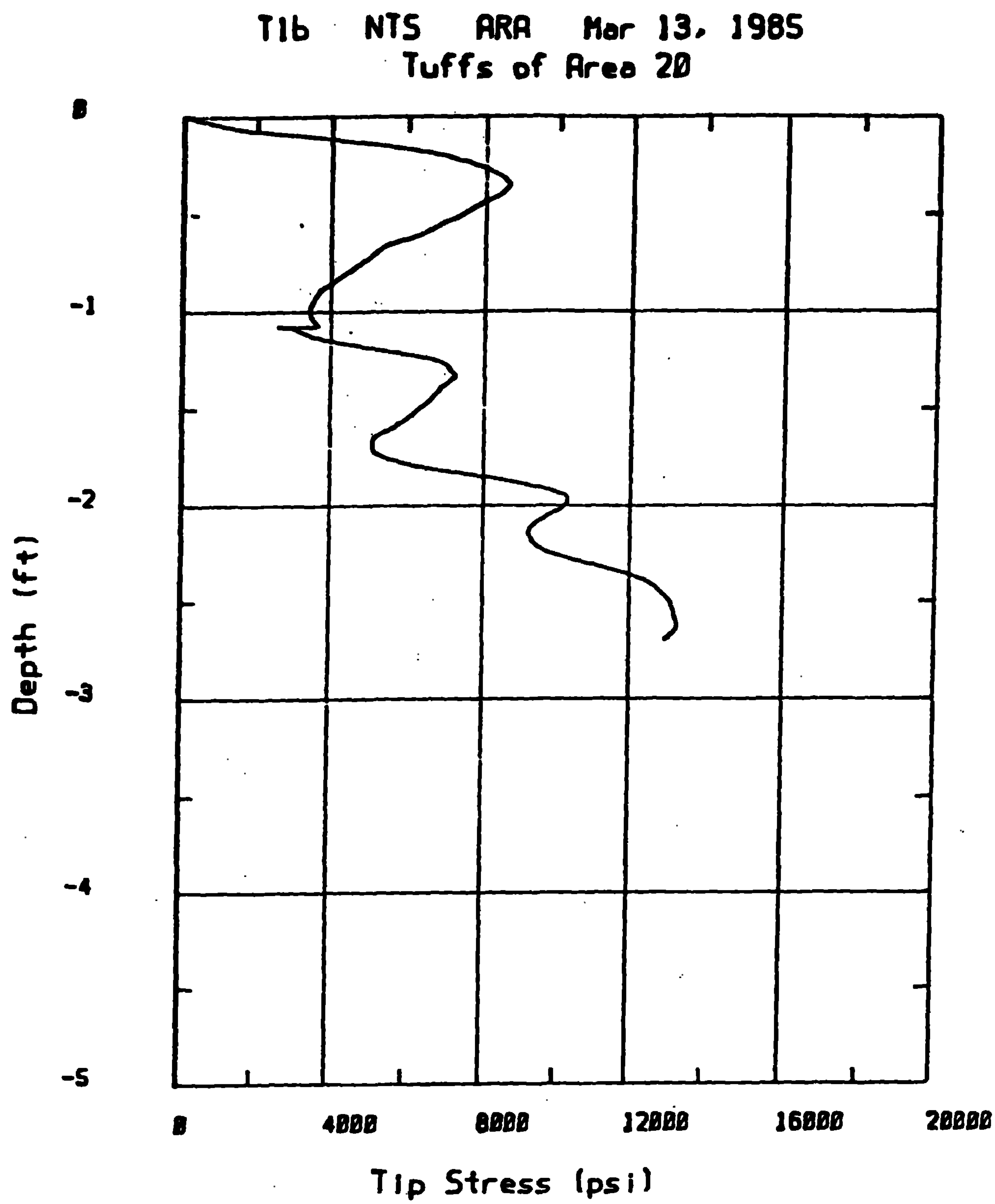

Figure 6b. Penetrometer tip stress vs depth for Site 8